

# **Status of ITk Pixel simulation and performance**

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# Outline

- The **ITk Layout Task Force** is approaching the point where a decision has to be taken between Pixel detector layout options
  - How to best extend coverage up to  $|\eta| = 4$  ?
- Status of **Pixel simulation + digitization**
  - Details of layouts under study
  - Pixel modules simulation, digitization model
- Status of **passive material** simulation
  - Much more realistic description than in Lol simulation, still a work in progress
- Status of **track reconstruction**
  - Single-pass tracking, improved ambiguity solver (CTIDE), photon conversions recovery
  - Latest results from Upgrade Tracking
- Discussion of **future goals** for the Layout Task Force
  - Layouts to simulate next

## Quick guide to the Layout Task Force

Step 1.0: First simulation in new design

Step 1.2: Major bugs fixed

Step 1.5: Updates in strips (we are here)

Step 1.6: Updates in material, reconstruction

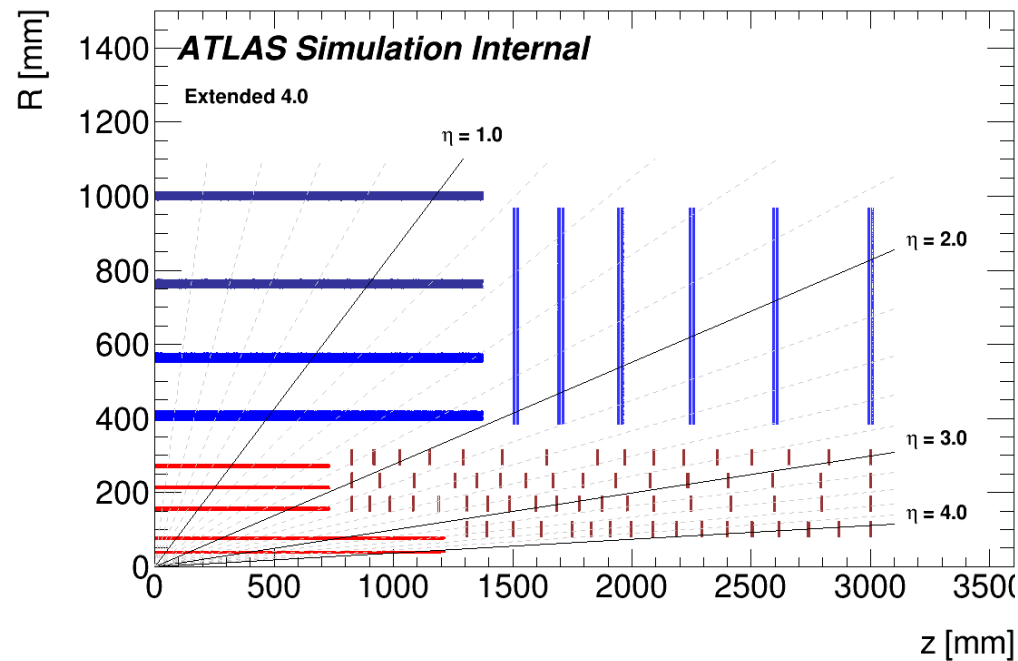
Step 2.0: Updates in pixels

Step 3.0: Post-decision

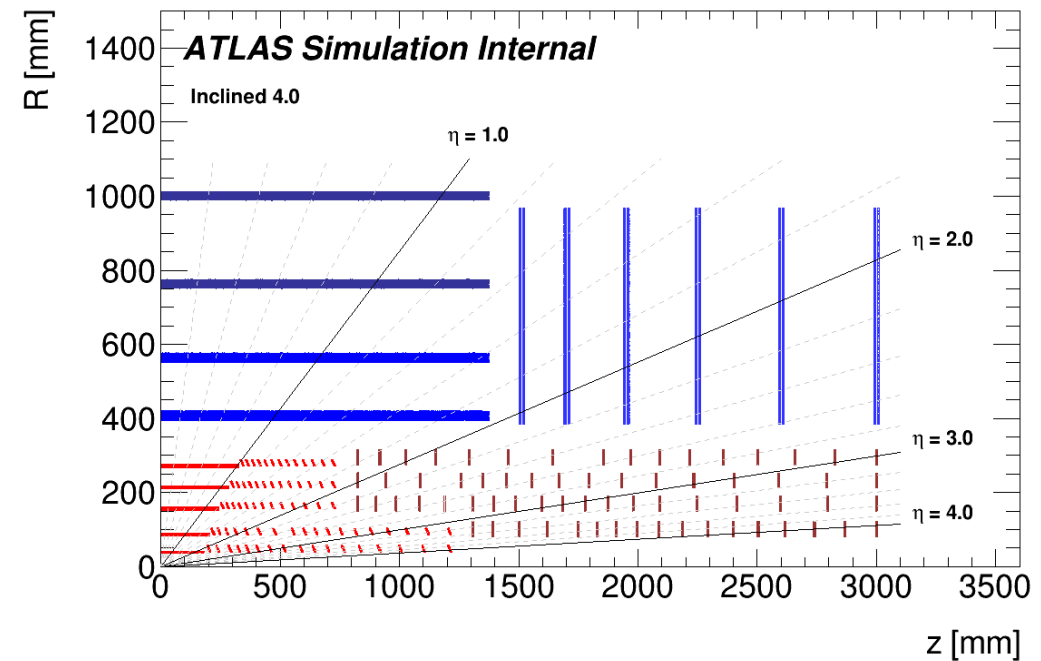
# Step 1.5 layouts, for Strips TDR and ECFA

- New figures with updated Strips layout will replace the ones previously available

Extended layout



Inclined layout



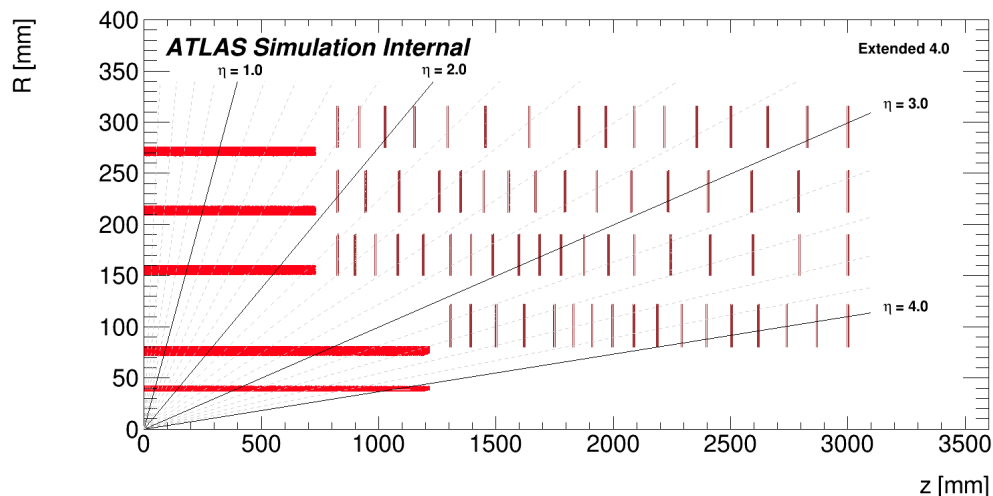
Parameters for each Layout TF Step are detailed in this document (TBU)

<https://svnweb.cern.ch/trac/atlasgroups/browser/Detectors/Upgrade/ITk/DetectorDescription/trunk/DetectorDescription.pdf>

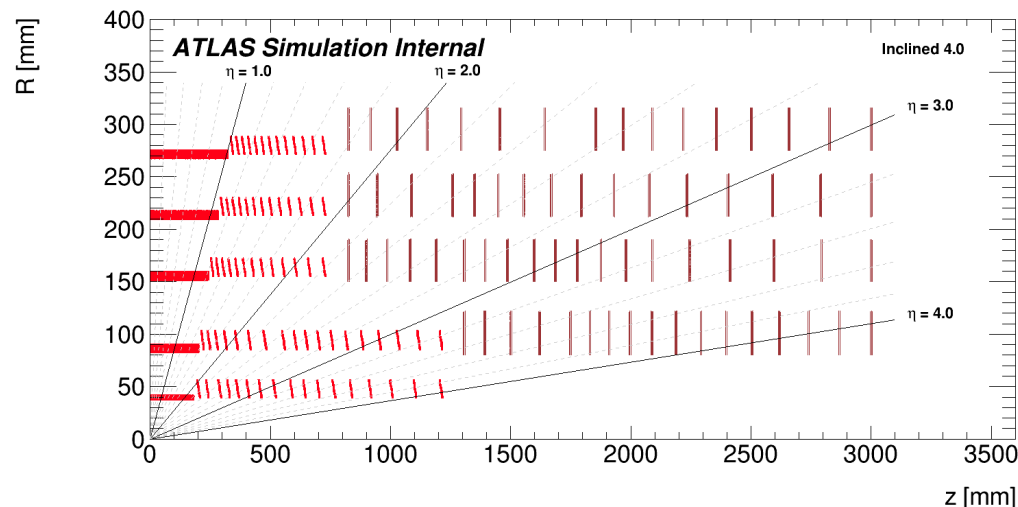
# Pixel layouts in Step 1.5

- Two layouts under evaluation, differing only in pixel barrel concept
  - Both are almost hermetic for  $|\eta| < 4$ ,  $|z_0| < 15$  cm
  - Extended** pixel barrel: conventional staves, long innermost two layers
  - Inclined** pixel barrel: forward modules tilted at  $56^\circ$  wrt beamline in all layers
  - Same endcap system based on modules placed in 4 ring layers, for both layouts
    - One ring layer is inside the Inner Support Tube to allow forward tracking, to be replaced along with the two innermost barrel layers after 5 years of HL-LHC

Extended layout



Inclined layout



# Pixel layouts in Step 1.5

- Layout specifications for Step 1

(stave tilt for flat section in both layouts = -14 degrees)

- Step 1.5 pixels are the same
- Barrel shown here

Inclined:

Flat section

Inclined section

Extended

Layer	Type	Modules per Half Stave	Half Stave Length [mm]	Staves	Radius [mm]	Stave Tilt [rad]
0	DoubleLength_RD53	4.5	1250	18	39	0
1	FourChip_RD53	5	1250	18	85	0
2	FourChip_RD53	6	780	32	155	0
3	FourChip_RD53	7	780	44	213	0
4	FourChip_RD53	8	780	54	271	0

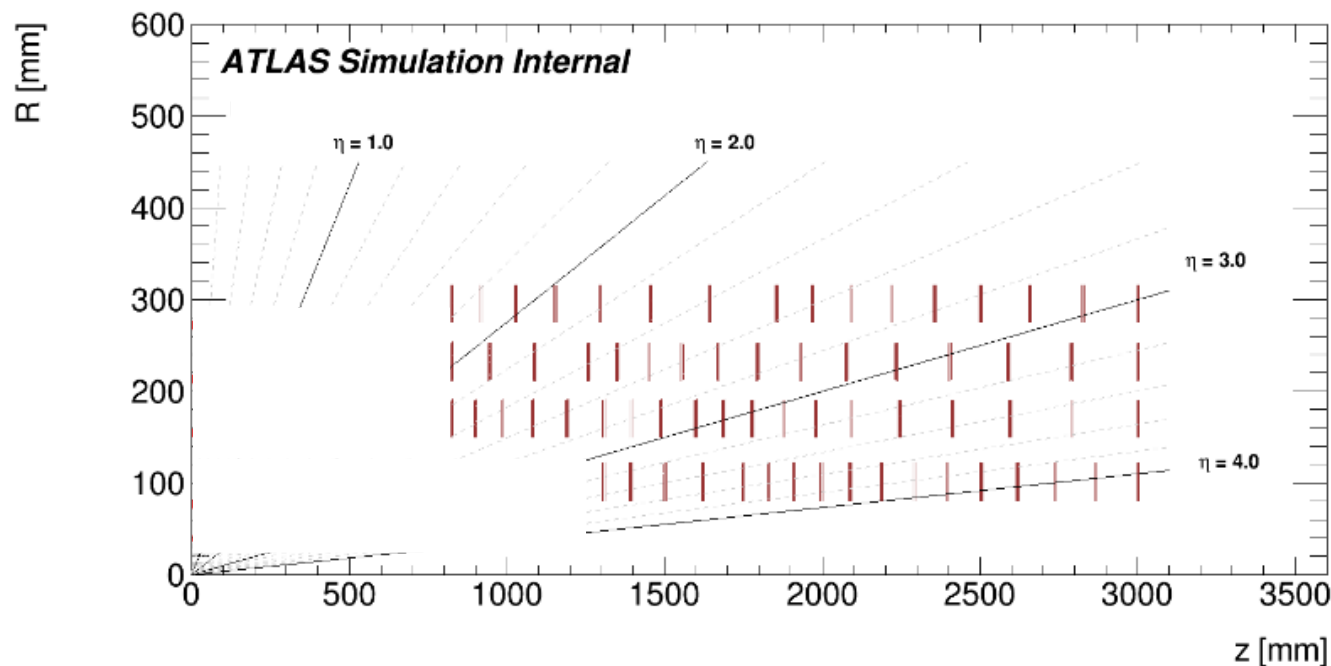
Layer	Type	Inclined positions on barrel stave [mm]									
Fully Inclined and Inclined											
0	SingleChip_RD53	197.8	234.1	285.8	322.8	359.7	403.1	454.0	513.9	584.2	
		638.4	696.4	760.9	832.4	911.9	1000.2	1098.1	1206.9		
		193.8	230.1	281.8	318.8	355.7	399.1	450.0	509.9	580.2	
		634.4	692.4	756.9	828.4	907.9	996.2	1094.1	1202.9		
1	DoubleWidth_RD53	214.4	240.7	272.2	309.9	355.1	409.2	473.9	551.5	599.9	
		646.5	697.3	752.7	813.0	878.8	950.5	1028.6	1113.7	1206.5	
		210.4	236.7	268.2	305.9	351.1	405.2	469.9	547.5	595.9	
		642.5	693.3	748.7	809.0	874.8	946.5	1024.6	1109.7	1202.5	
Fully Inclined only											
2	DoubleWidth_RD53	254.1	275.9	300.0	326.4	355.4	387.3	422.4	461.0	503.4	
		550.0	601.3	657.6	719.6						
		250.1	271.9	296.0	322.4	351.4	383.3	418.4	457.0	499.4	
		546.0	597.3	653.6	715.6						
3	DoubleWidth_RD53	295.7	318.6	343.2	369.7	398.1	428.8	461.8	497.2	535.4	
		576.5	620.7	668.3	719.5						
		291.7	314.6	339.2	365.7	394.1	424.8	457.8	493.2	531.4	
		572.5	616.7	664.3	715.5						
4	DoubleWidth_RD53	336.7	359.5	383.5	409.1	436.1	464.8	495.1	527.3	561.4	
		597.5	635.8	676.4	719.4						
		332.7	355.5	379.5	405.1	432.1	460.8	491.1	523.3	557.4	
		593.5	631.8	672.4	715.4						

Layer	Type	Modules per Half Stave	Half Stave Length [mm]	Staves	Radius [mm]
0	DoubleLength_RD53	30	1218	16	39
1	FourChip_RD53	30	1218	16	75
2	FourChip_RD53	18	731	32	155
3	FourChip_RD53	18	731	44	213
4	FourChip_RD53	18	731	54	271

# Pixel layouts in Step 1.5

- Endcap shown here (identical for all layouts → will be re-optimized for Step 2)

Ring layer	Type	# Sectors	Radius [mm]	Ring positions
0	FourChip_RD53	24	80	1308 1391 1501 1620 1750 1830 1910 1997 2088 2188 2292 2397 2503 2618 2740 2867 3000
1	FourChip_RD53	36	150	823 899 986 1082 1189 1308 1394 1486 1598 1685 1778 1876 1980 2090 2246 2414 2596 2793 3000
2	FourChip_RD53	48	212.5	823 944 1088 1258 1349 1448 1554 1669 1794 1929 2075 2233 2404 2589 2790 3000
3	FourChip_RD53	60	275	823 918 1027 1151 1294 1456 1642 1854 1968 2089 2217 2355 2502 2658 2825 3000



# Pixel modules in Step 1.5

- Digitization model the same as for FEI4, except with different parameters
  - Pixel size  $50 \times 50 \mu\text{m}^2$ , sensor thickness  $150 \mu\text{m}$  everywhere
  - Reverse bias  $150 \text{ V}$ , temperature  $-10 \text{ C}$
  - Chip thickness  $150 \mu\text{m}$ , threshold  $600e$
  - Time-walk simulation and compensation disabled

Type	Chip		Pitch		Rows	Cols
	length	width	eta	phi		
RD53	20.0	16.8	0.050	0.050	336	400
RD53_25x100	20.0	16.8	0.100	0.025	672	200

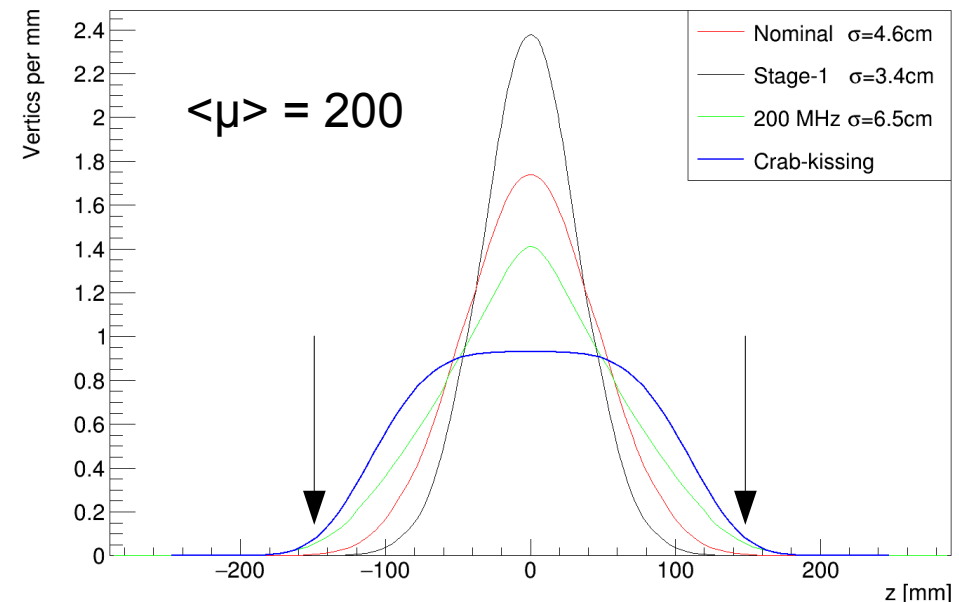
Table 1: Pixel front-end chip specifications, all lengths in mm. Note that in reality the same RD53 front-end chip would be used, and the pixel pitch is a property of the sensor. *ITK\_PixelModules.xml*

- Multi-chip modules are simulated by combining single-chip modules
  - Instead of “long pixels” in gaps between chips, simulate extra channels for now (easier)

Module	Chip type	Length in chips	max width in chips	sensor thickness	chip thickness	hybrid thickness
SingleChip_RD53	RD53	1	1	0.150	0.150	0.0
DoubleLength_RD53	RD53	2	1	0.150	0.150	0.0
DoubleWidth_RD53	RD53	1	2	0.150	0.150	0.0
FourChip_RD53	RD53	2	2	0.150	0.150	0.0

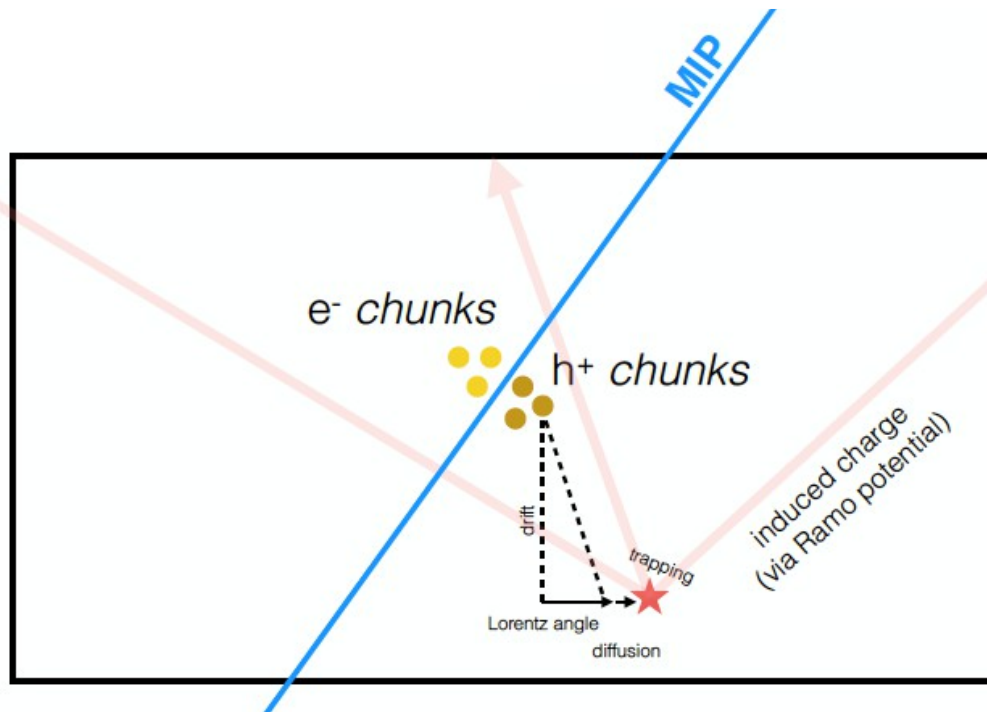
# Main future goals for ITk Pixel simulation

- Update pixel layout
  - Innermost barrel layer radius
  - Innermost endcap ring layer radius (inside IST), needed for tracking up to  $|\eta| = 4$
  - Number of modules in endcaps
  - Ensure full hermeticity for  $|\eta| < 4$ ,  $|z_0| < 20$  cm
    - Some beam profile scenarios considered go beyond  $|z_0| = 15$  cm
- Pixel sensor studies
  - $25 \times 100 \mu\text{m}^2$  pitch
  - Reduce planar sensor thickness to  $100 \mu\text{m}$  inside IST (radiation hardness)
  - Need to start studying 3D modules in forward pixel barrel
  - CMOS simulation almost ready for first integration in release 20.20

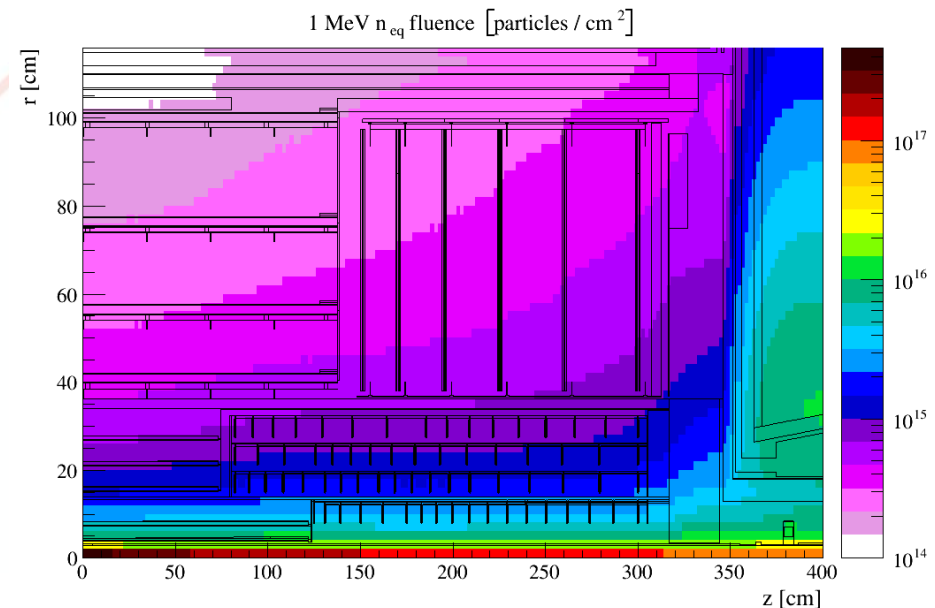


# Main future goals for ITk Pixel simulation

- Radiation damage
  - Currently all ITk simulations are without any radiation damage
  - New pixel digitization tool was developed with AllPix, being ported in Athena
    - Working points proposal for  $3000 \text{ fb}^{-1}$
    - Fluences  $2\text{e}16, 1\text{e}16, 5\text{e}15, 1\text{e}15 \text{ n}_{\text{eq}}/\text{cm}^2$  ; bias 800 V (150 V un-irradiated)

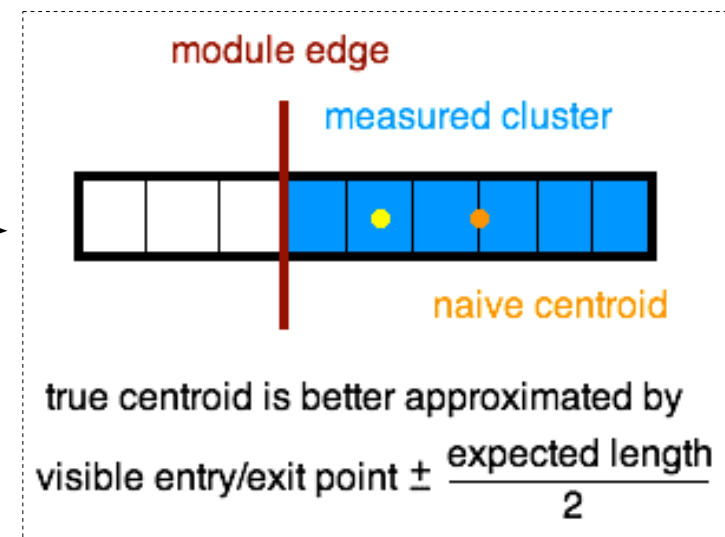
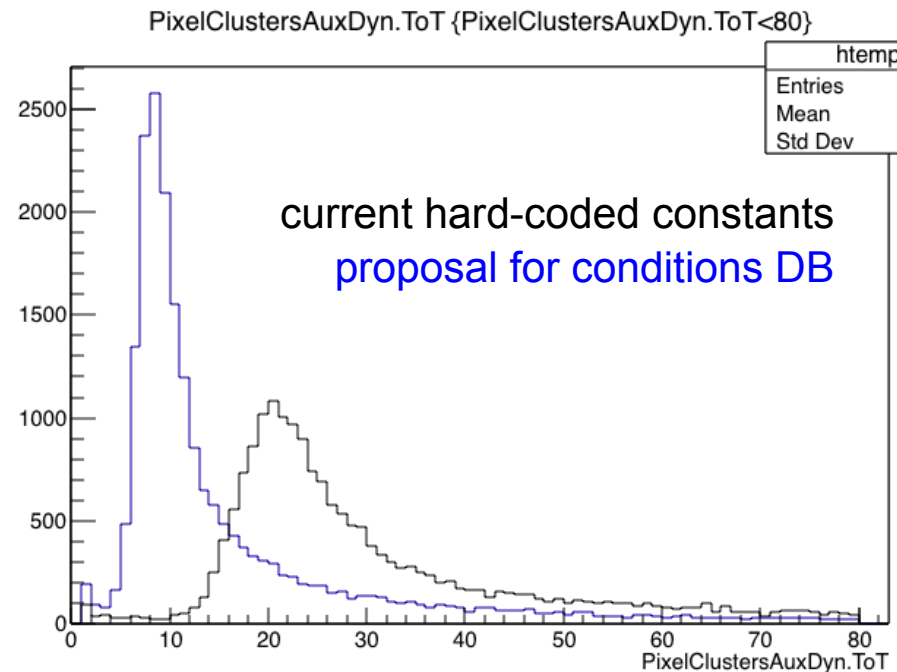


Latest FLUKA results  
(need to improve description in FLUKA model)



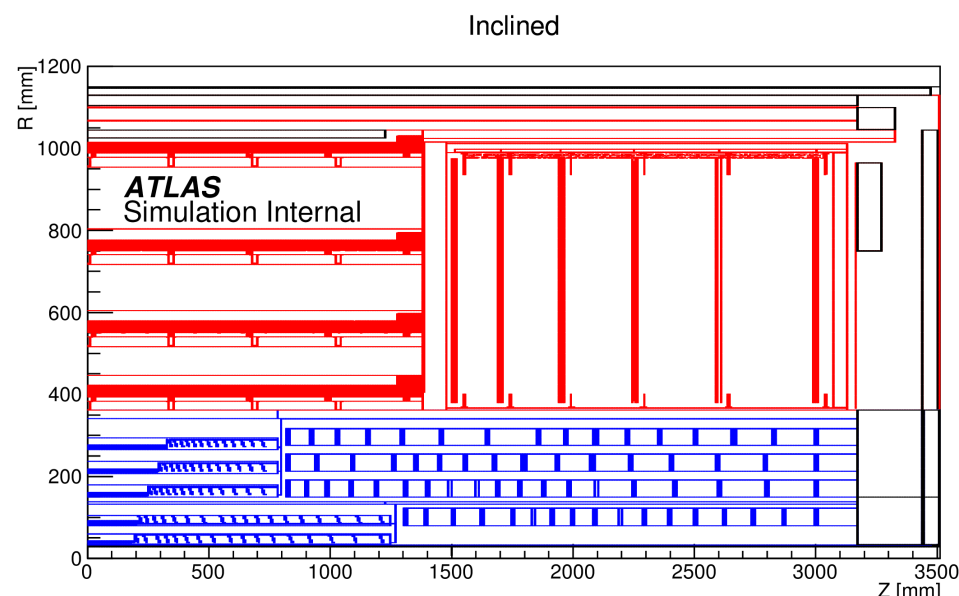
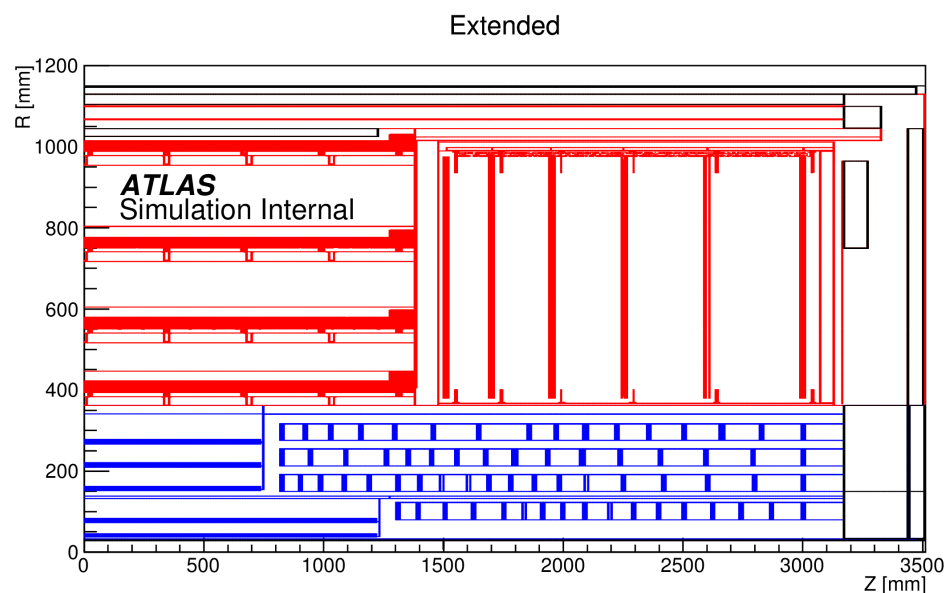
# Main future goals for ITk Pixel simulation

- More realistic ToT
  - Update to PixelConditions proposed to emulate 4-bit ToT →
  - Question: should we instead keep simulating 8-bit ToT, and truncate at analysis-level?
- Robustness
  - Identify possible failure modes
  - Disable randomly staves / rings, modules, individual channels
- Improved cluster centroid positions
  - Long clusters in extended layouts
    - on module edge residuals need to be fixed →
    - off module edge: local  $\theta$  measurement in track fit requires Kalman filter
  - Long term: analog clustering and/or neural networks
    - will probably only develop for the chosen layout



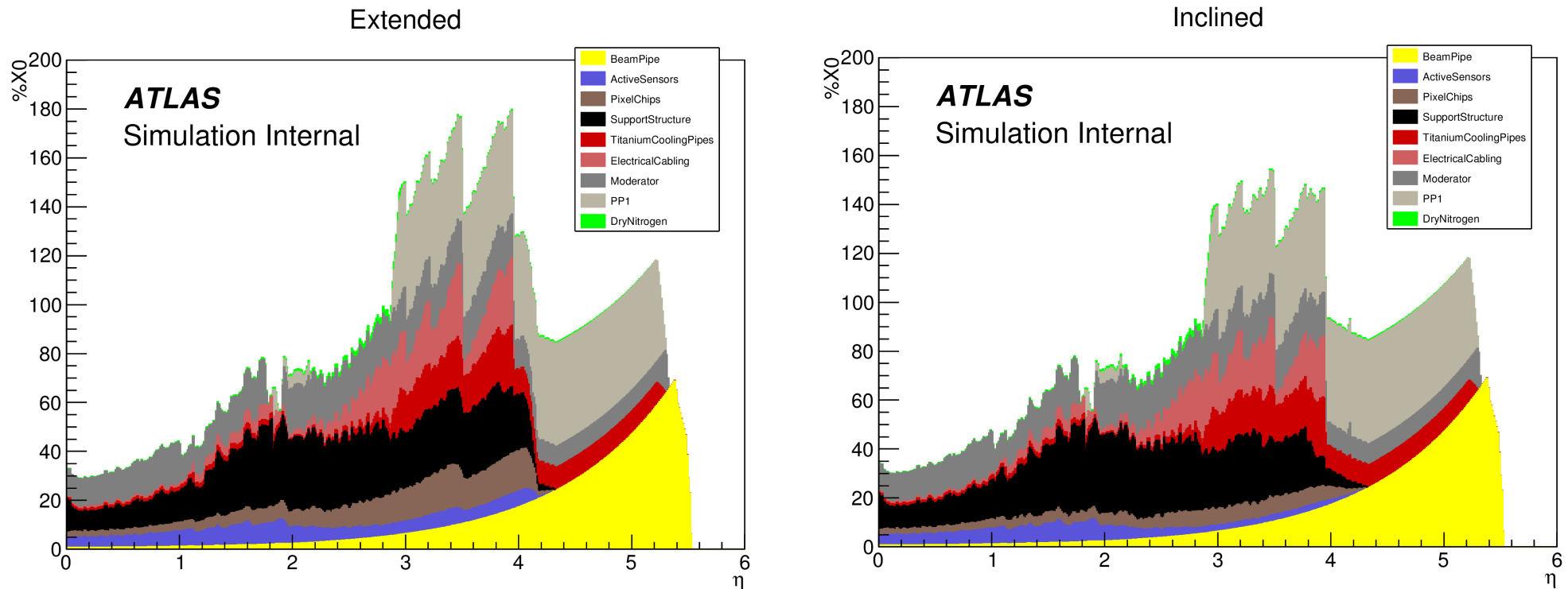
# Passive material in Step 1.5

- Description of passive material for both pixels and strips is much improved compared with Lol, Lol-VF and Scoping Document implementations
  - But not perfect!
- Baseline pixel barrel implementations based on total mass
  - Extended layout: I-beams
  - Inclined layout: SLIM Longerons (heaviest possibility)
    - Alpine and SLIM Truss also available and maintained in simulation framework
- Endcap implementation in close collaboration with designers



# Passive material for Step 1.5

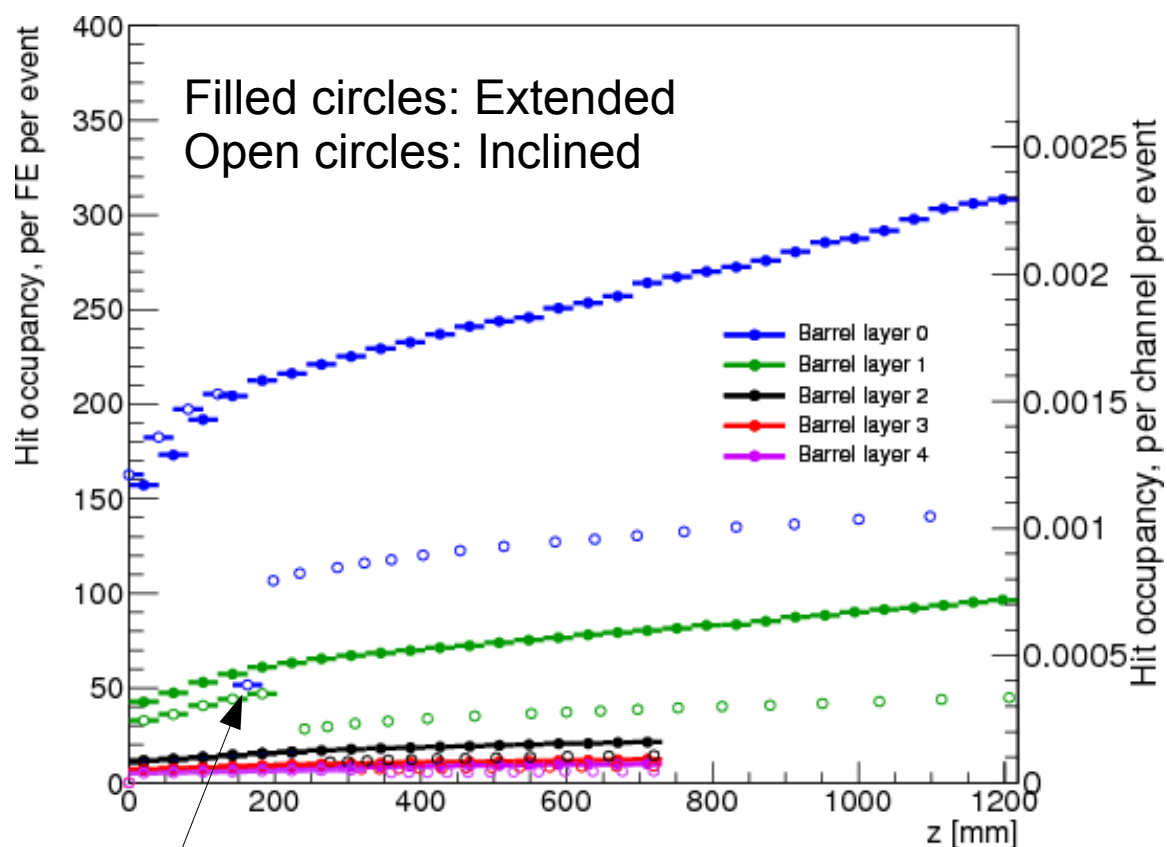
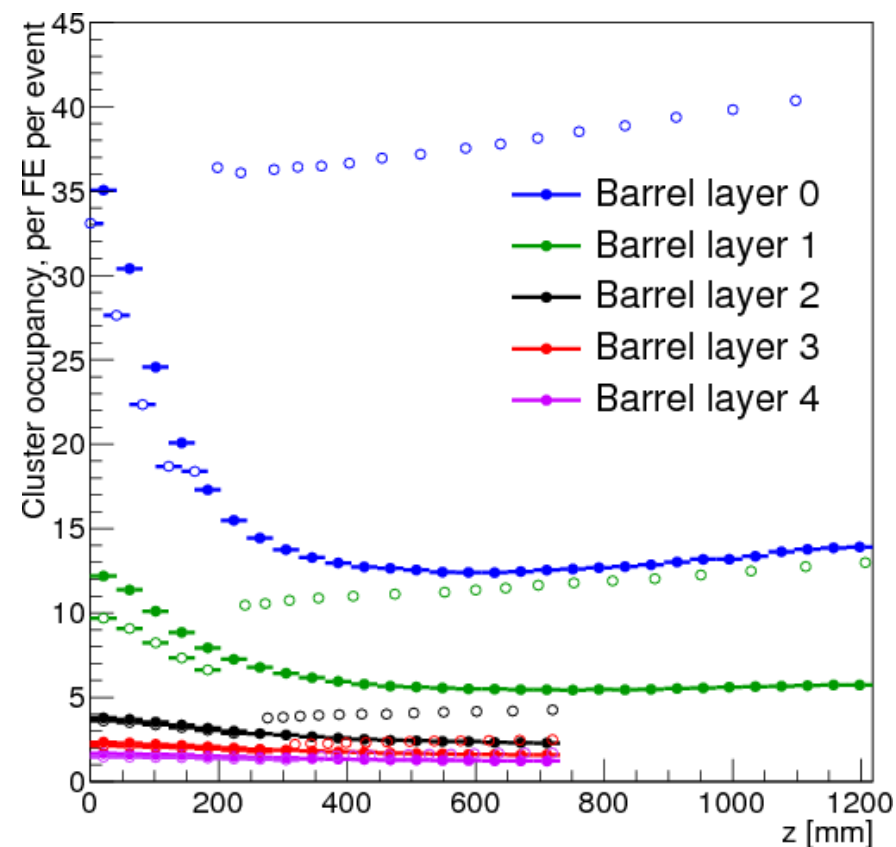
- Material broken down by source
  - Total  $X_0$  is similar between layouts. Also plan to run simulation with a factor 2 more



- Main caveats to fix in next iteration:
  - Pixel chips have more than double the  $X_0$  they should have
  - Local supports for inclined modules are integrated in stave mass
  - Need to model flat sections vs. inclined sections of inclined barrel separately
  - PP1 simulation with more details, currently homogeneous 20 kg block

# Pixel occupancy studies

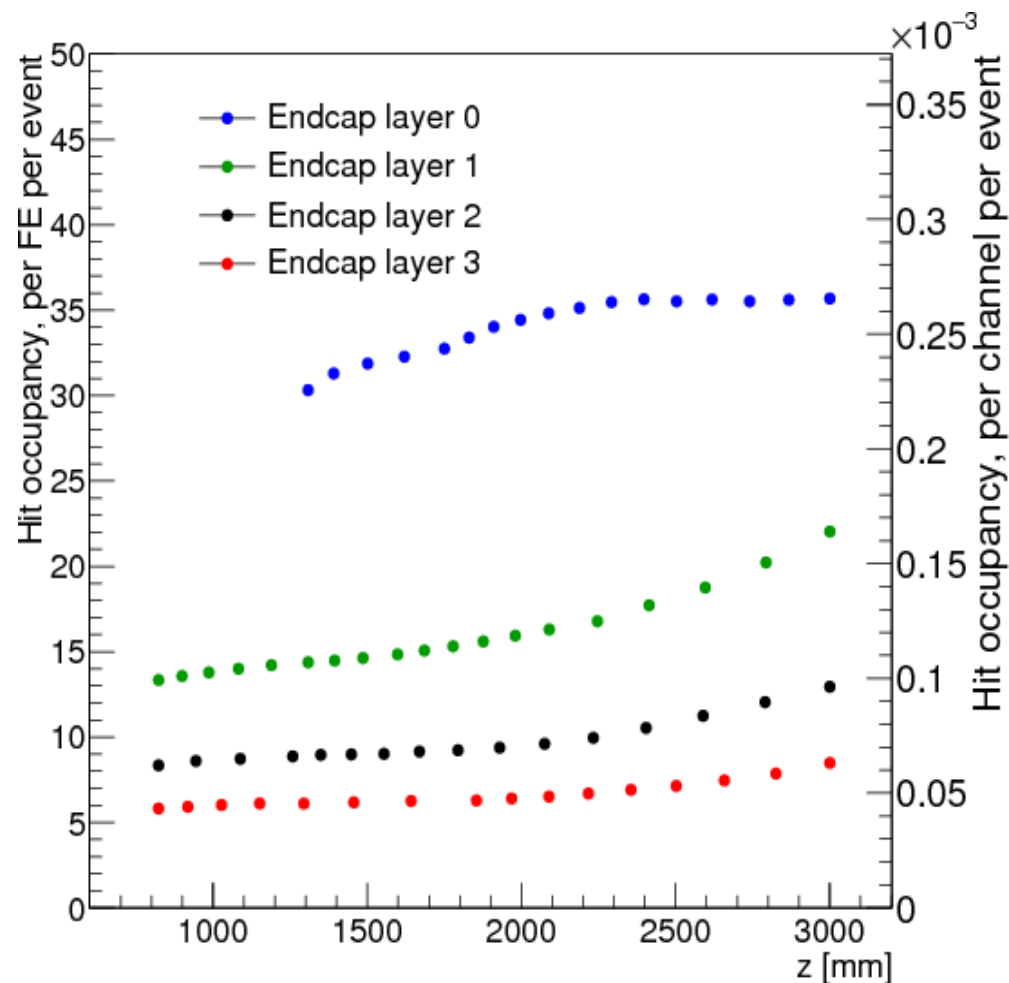
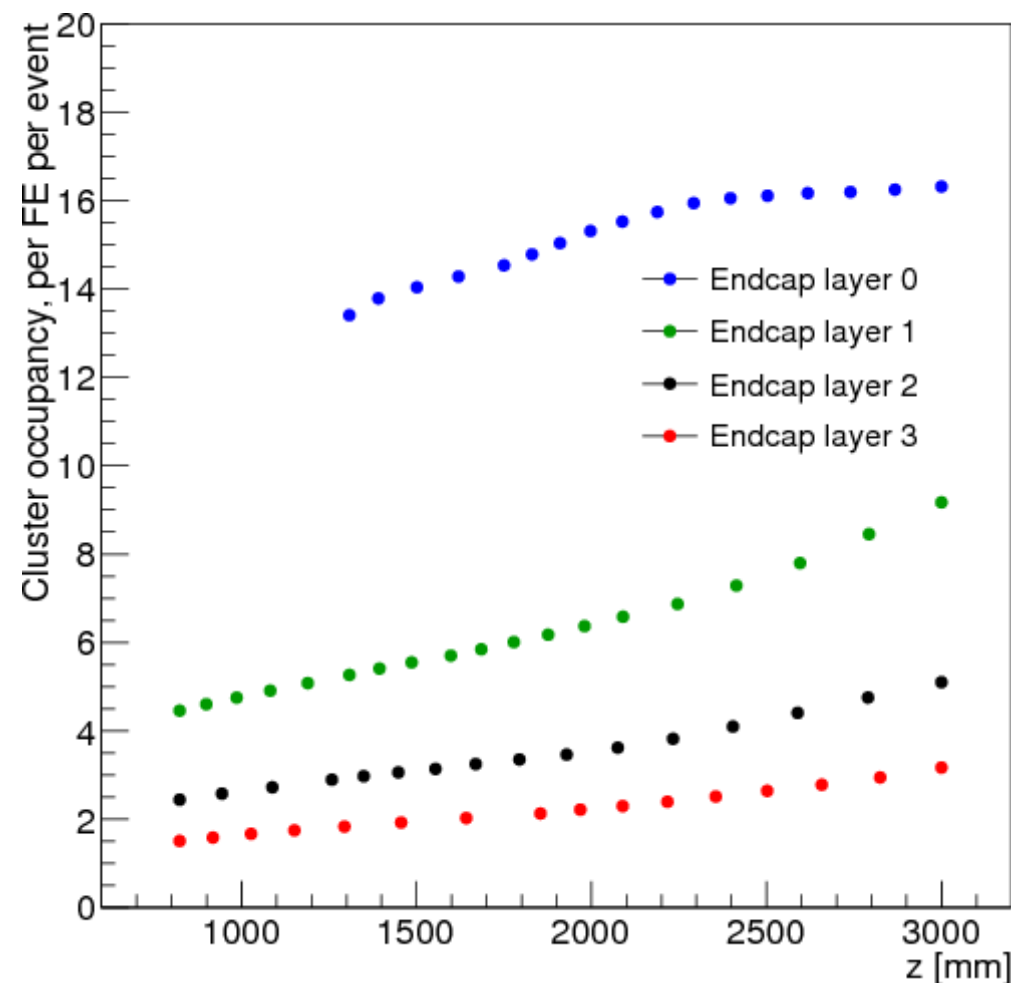
- Cluster and hit occupancy in pixel barrel FE
  - Min-bias samples,  $\langle\mu\rangle = 200$
  - In inclined forward barrel, hit occupancies are lower, cluster occupancies are higher



(double-chip module as denominator here, should be single-chip)

# Pixel occupancy studies

- Cluster and hit occupancy in pixel endcap FE
  - Min-bias samples,  $\langle \mu \rangle = 200$
  - Here pixel size is generally small, so clusters and hits follow the same trends



# Reconstruction improvements

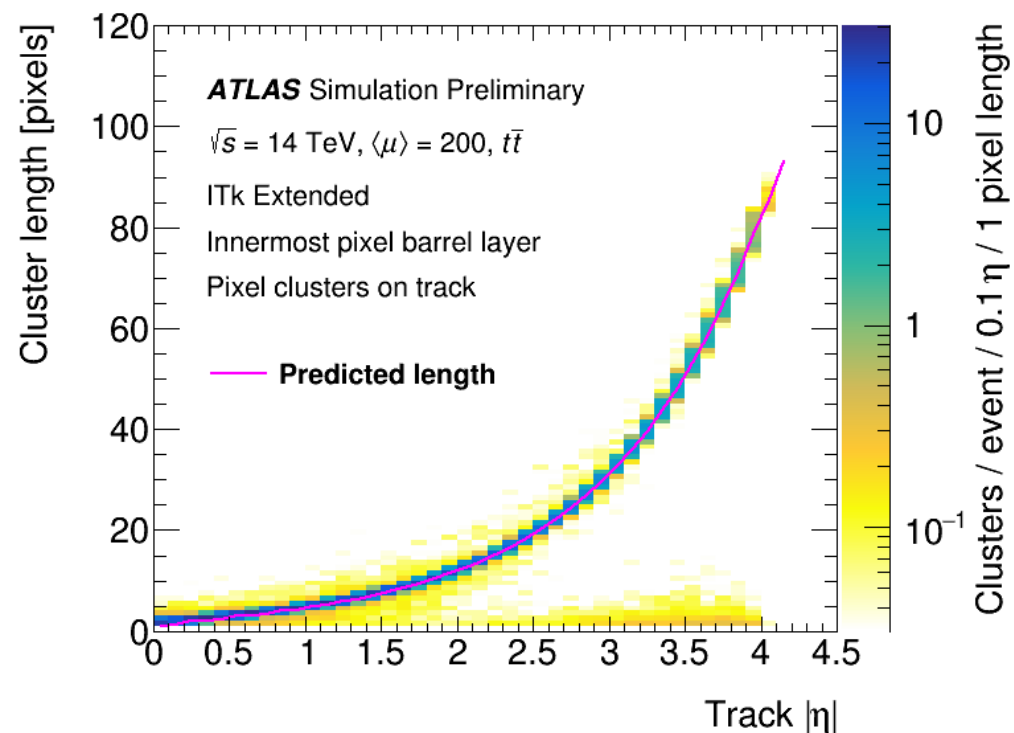
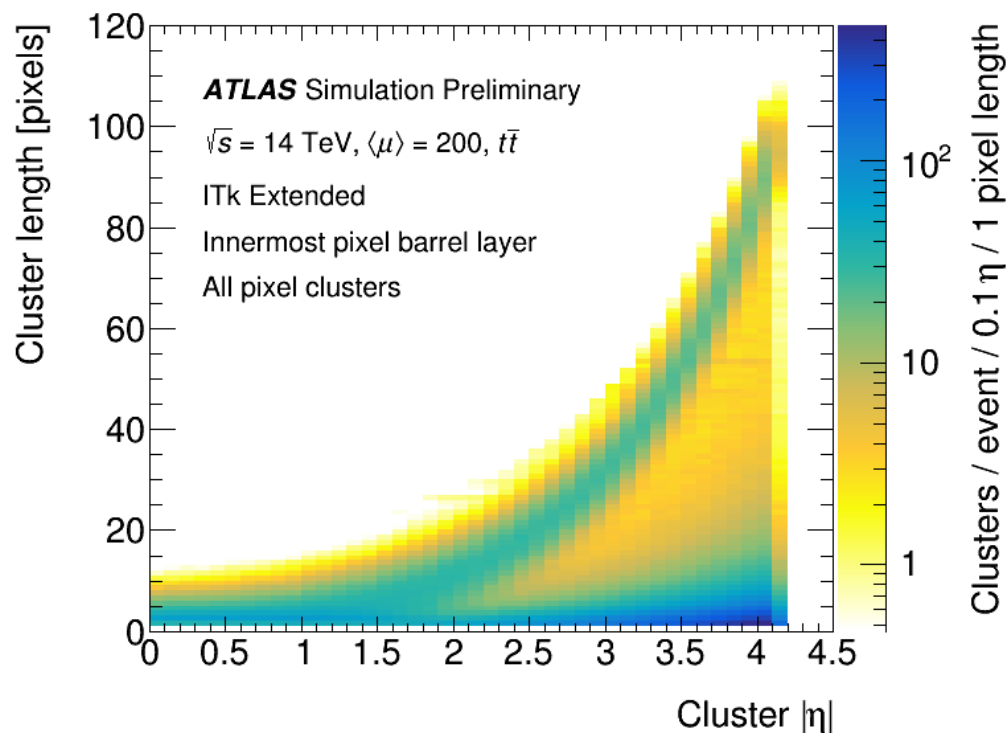
- Introducing single-pass tracking for ITk
  - Previously tracking done once for  $|\eta| < 2.7$ , then for  $2.4 < |\eta| < 4$  with duplicate removal
  - Cluster requirements ~ the number of expected clusters without phi overlap, minus two

Extended layout				Inclined layout		
Requirement	Pseudorapidity interval			Requirement	Pseudorapidity interval	
	$ \eta  < 2.7$	$2.7 <  \eta  < 3.4$	$3.4 <  \eta  < 4.0$		$ \eta  < 2.7$	$2.7 <  \eta  < 4.0$
Silicon hits	$\geq 9$	$\geq 7$	$\geq 6$	Silicon hits	$\geq 9$	$\geq 9$
Pixel hits	$\geq 1$	$\geq 1$	$\geq 1$	Pixel hits	$\geq 1$	$\geq 1$
Holes	$< 3$	$< 3$	$< 3$	Holes	$< 3$	$< 3$
Pixel holes	$< 2$	$< 2$	$< 2$	Pixel holes	$< 2$	$< 2$
Strip holes	$< 3$	$< 3$	$< 3$	Strip holes	$< 3$	$< 3$
$p_T$ [MeV]	$> 900$	$> 400$	$> 400$	$p_T$ [MeV]	$> 900$	$> 400$
$ d_0 $	$\leq 2 \text{ mm}$	$\leq 10 \text{ mm}$	$\leq 10 \text{ mm}$	$ d_0 $	$\leq 2 \text{ mm}$	$\leq 10 \text{ mm}$
$ z_0 $	$\leq 25 \text{ cm}$	$\leq 25 \text{ cm}$	$\leq 25 \text{ cm}$	$ z_0 $	$\leq 25 \text{ cm}$	$\leq 25 \text{ cm}$

- Now emulating the improved ambiguity solver from Run 2
- Extended layout: dedicated long pixel clustering and pattern recognition
  - Option to merge clusters across gaps, and reduction in number of seeds (next slide)
  - Shortcomings found with cluster centroid positions discussed earlier, work in progress

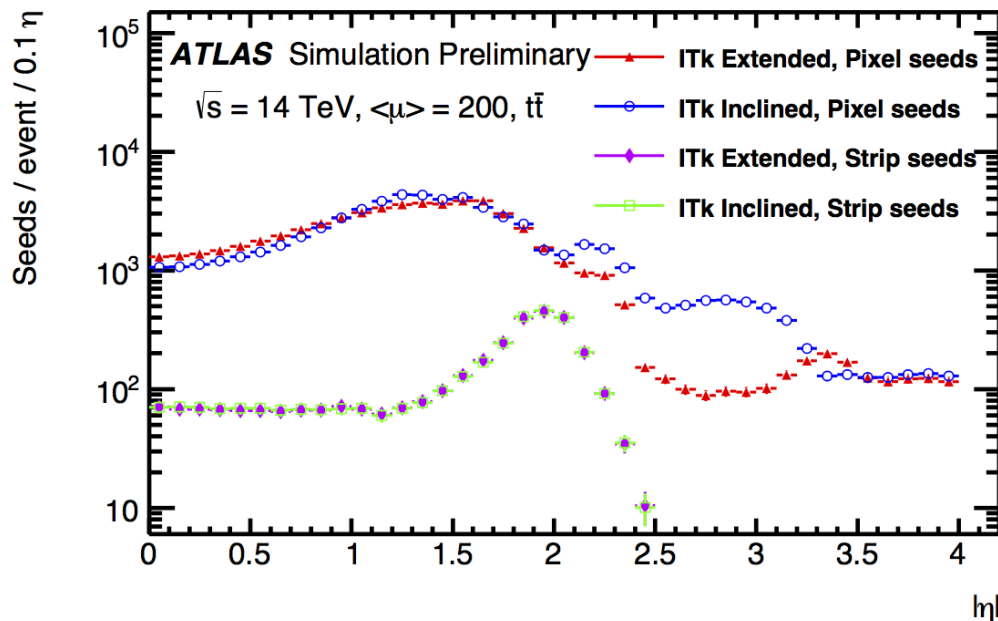
# Upgrade Tracking results

- Distribution of cluster length in Extended layout
  - Length of clusters on track generally match expected length
    - small population of short clusters on track is another confirmation that improvements are needed

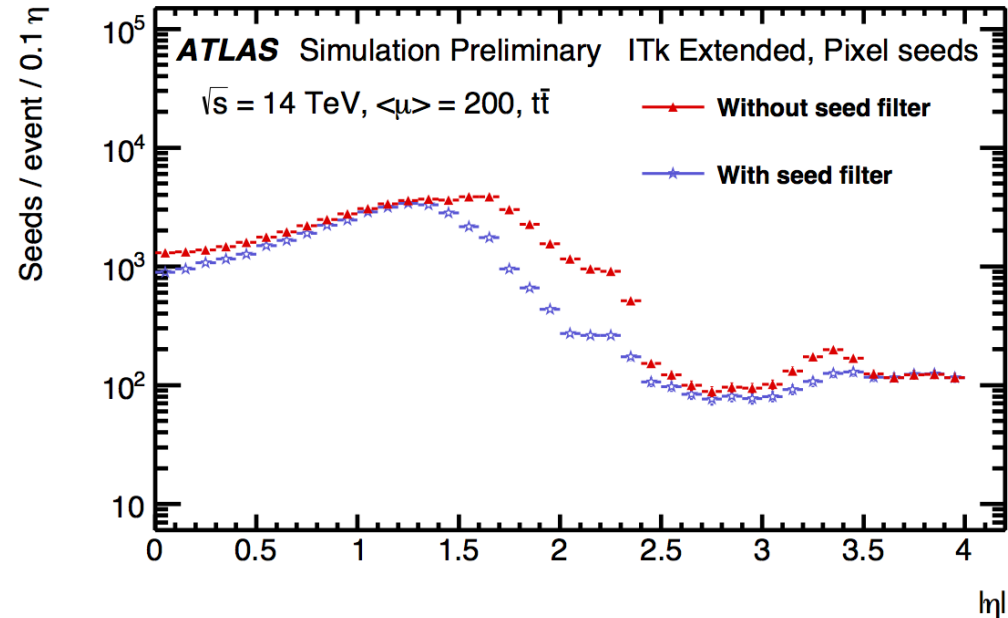


# Upgrade Tracking results

- Number of seeds is lower in Extended layout
  - Only PPP and SSS seeds; max extrapolation distance 40 cm
    - Current algorithms don't make optimal use of long clusters at seeding stage
- Does not immediately translate into lower CPU time (next slide)

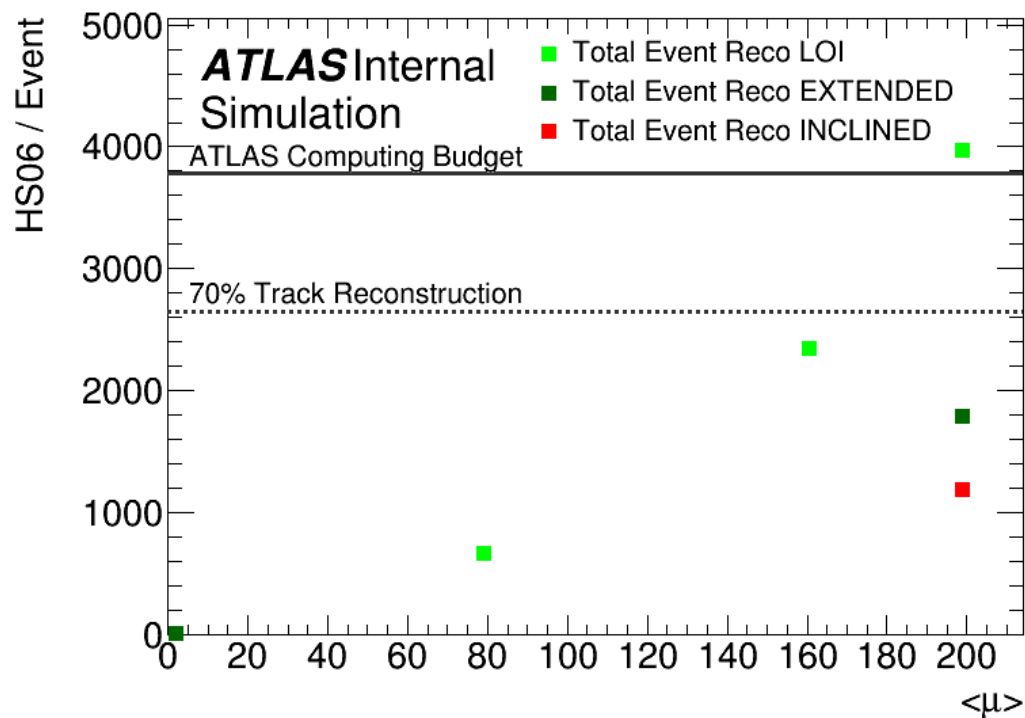


(this plot without seed filter)

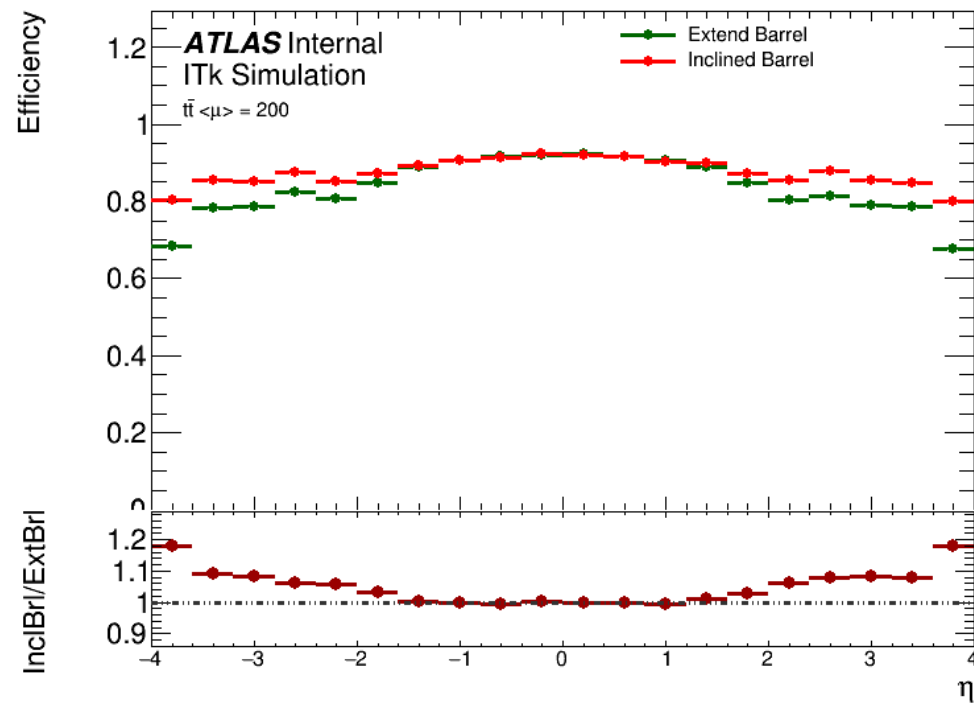


# Upgrade Tracking results

- Computing time is well within budget
  - Reconstruction takes longer for Extended because clustering and pattern recognition algorithms with long clusters are slow (there is much room for speed optimization)
- Tracking efficiency currently lower for Extended
  - Long cluster centroid improvements expected to improve matching to track candidates



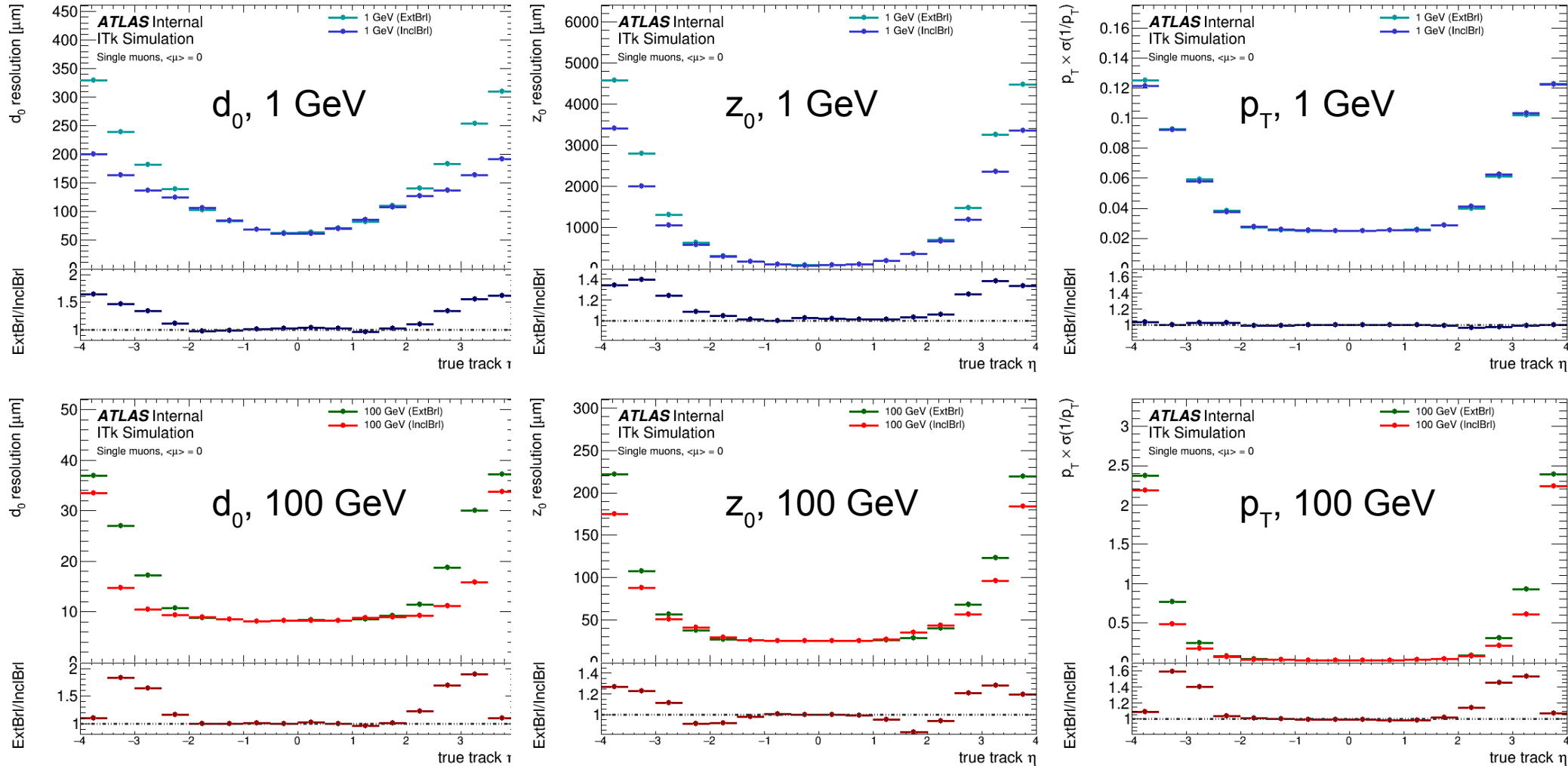
Run 2 at  $\langle \mu \rangle = 200$ :  
20000 HS06 / event



# Upgrade Tracking results

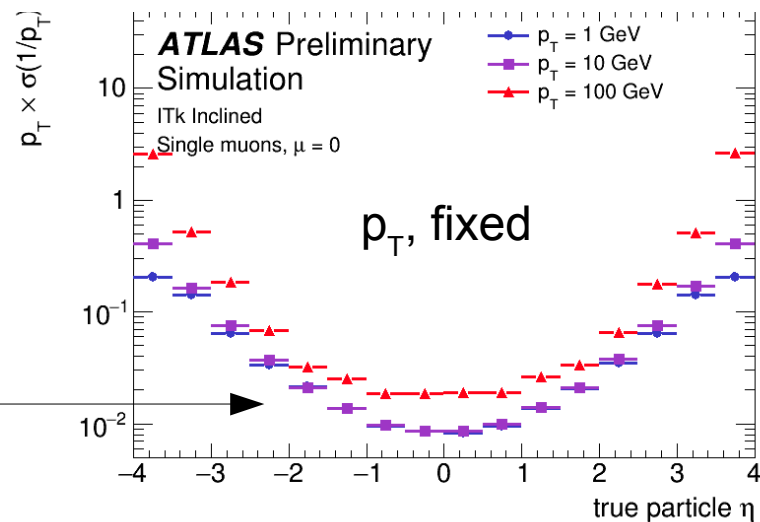
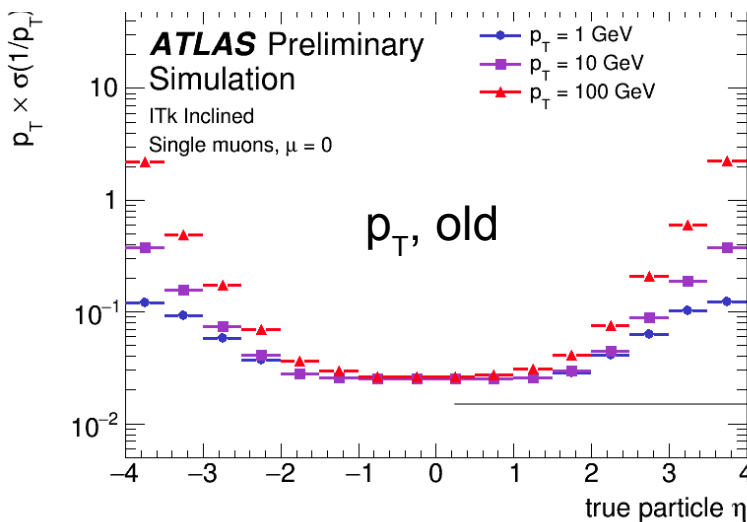
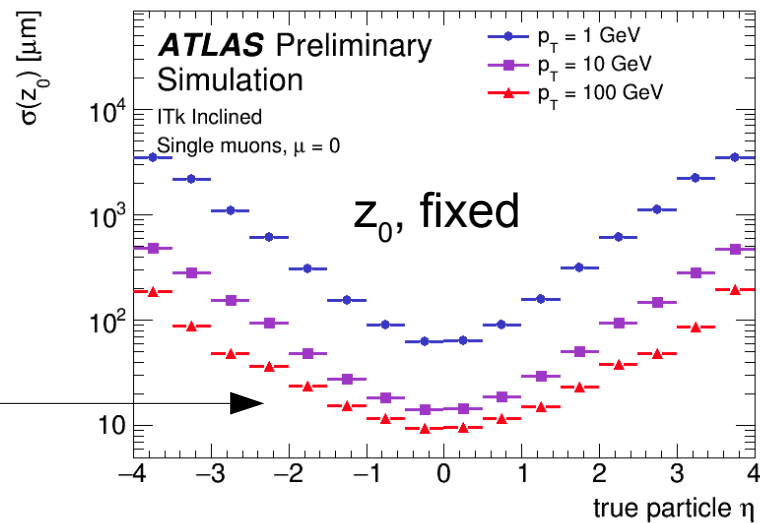
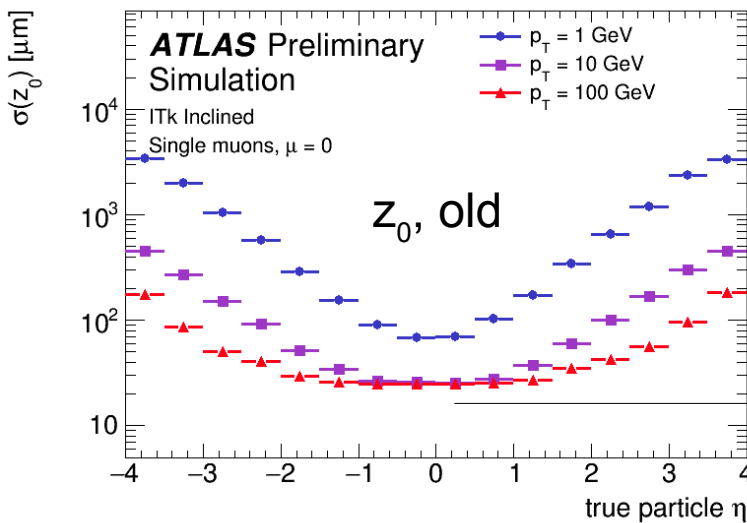
- In general the single-muon resolution is comparable for  $|\eta| < 2$ 
  - Inclined seems to do better for  $2 < |\eta| < 4$ ; to be verified in Step 1.6

**Caveat:**  
see next slide



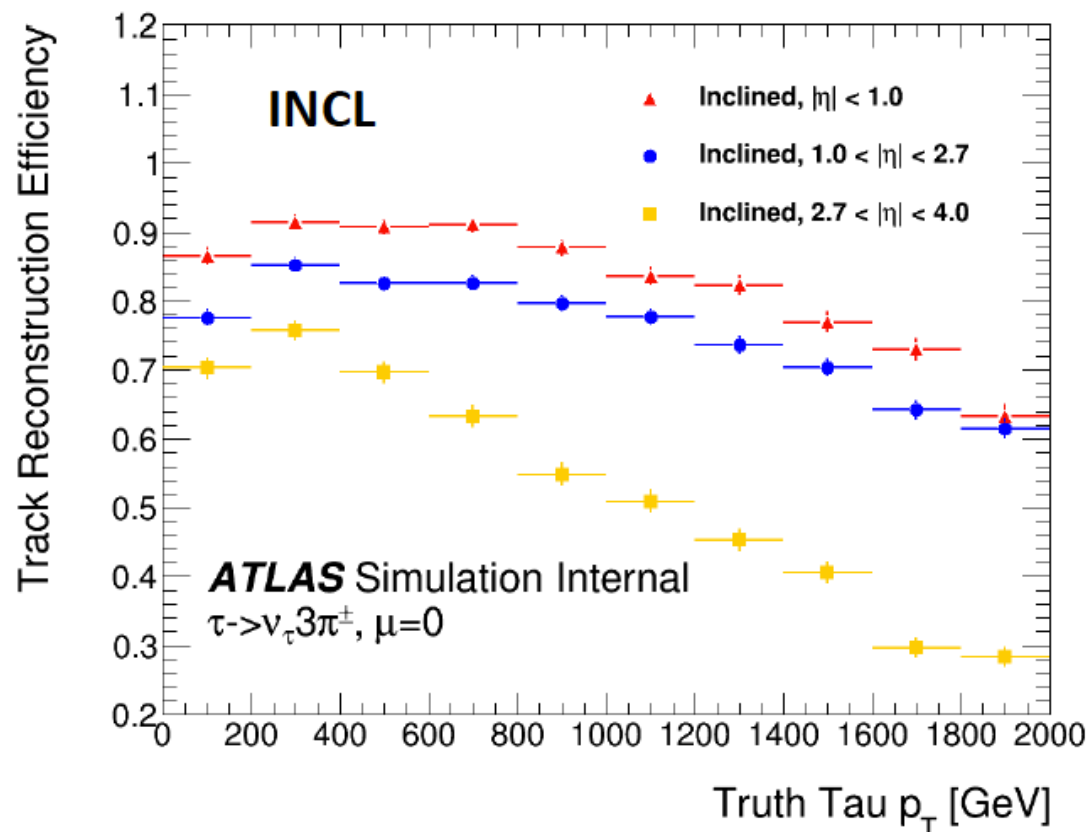
# Upgrade Tracking results

- Caveat: bug found in 1D projections in  $\eta$  bins used to calculate resolutions
  - Affects central region for  $z_0$  and  $p_T$ , shown here for Inclined
  - Fixed for ECFA public result to be released this Wednesday



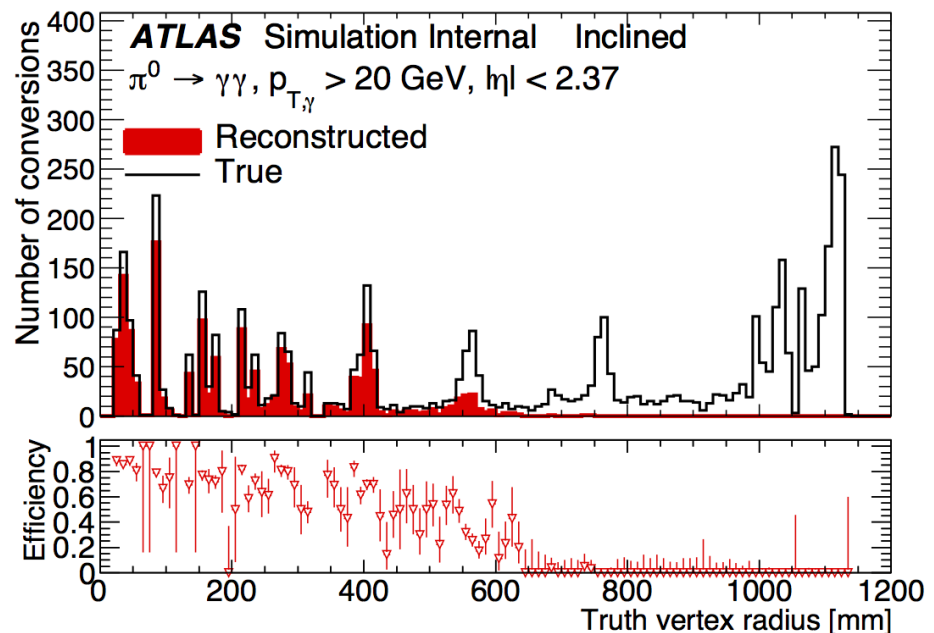
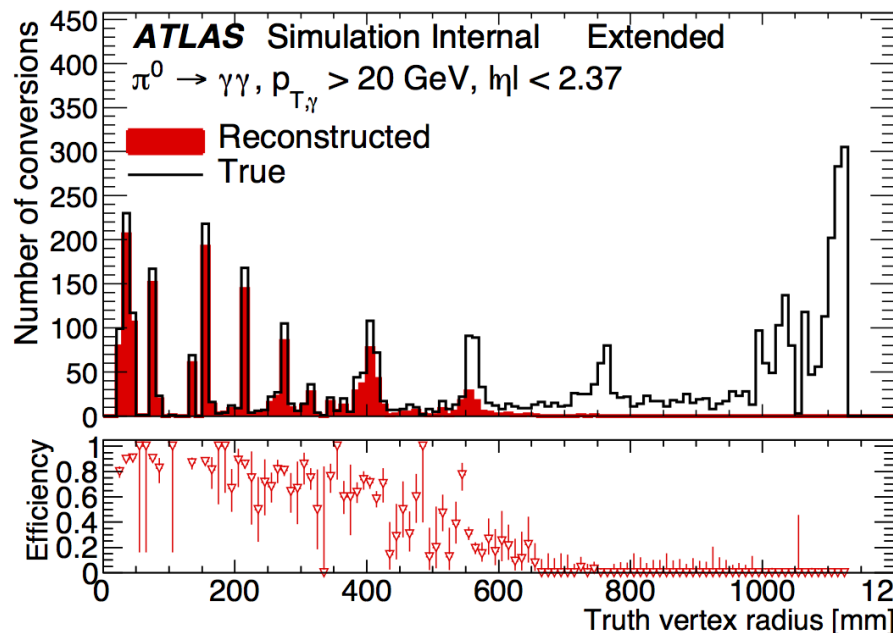
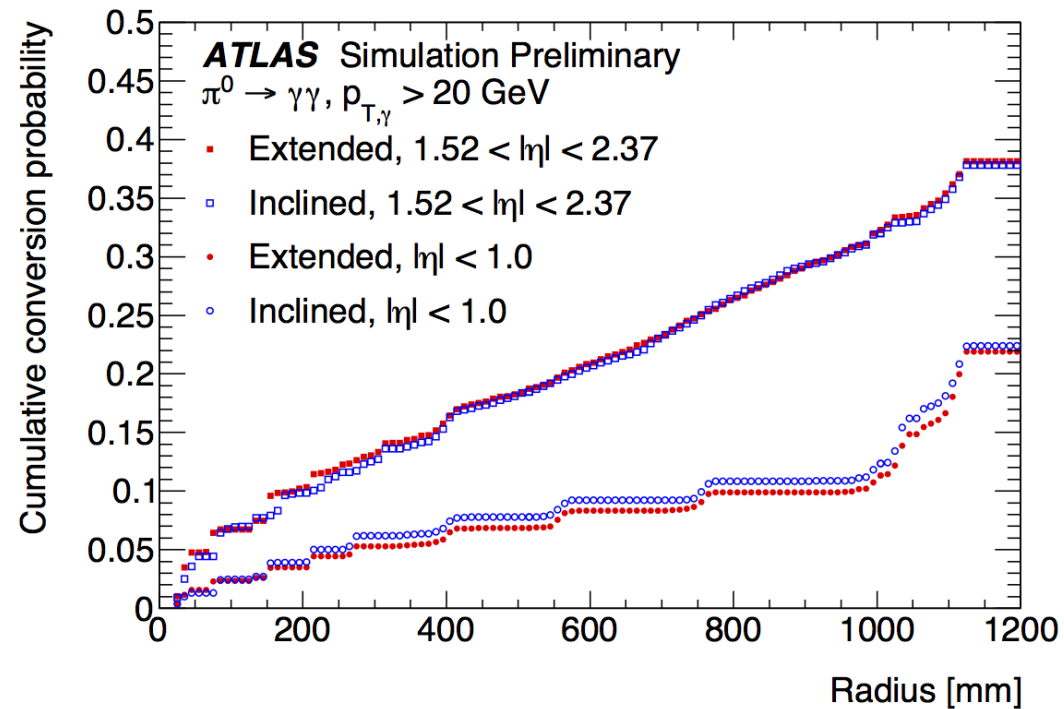
# Upgrade Tracking results

- Tracking in dense environments
  - Efficiency to reconstruct all three charged pions in 3-prong decay of single  $\tau$  without pileup as function of  $\tau$  lepton  $p_T$
  - Meets requirements for the Inclined layout
  - Long clusters need to be understood better before we can make this plot for Extended



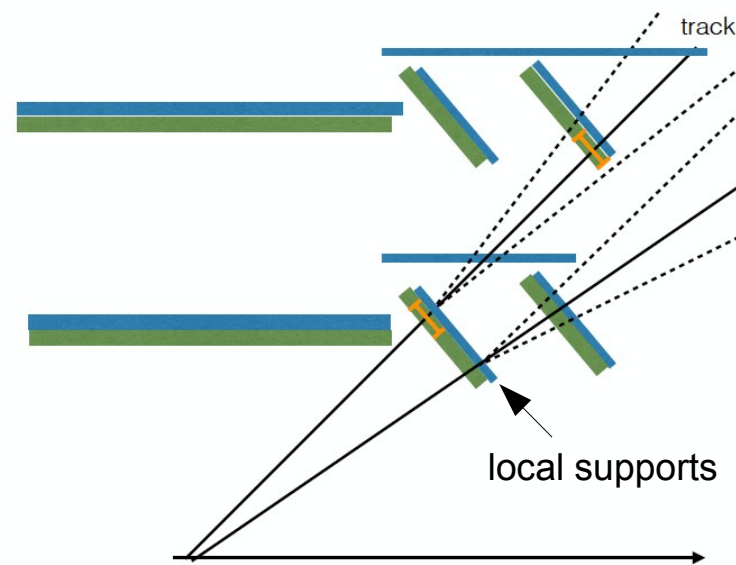
# Upgrade Tracking results

- First attempt at photon conversions recovery in ITk
  - Simple strategy: run additional pass of tracking with loosened requirements (off by default)
  - Good efficiency in both layouts
  - Needs to be improved by considering only ROI from calo



# Future goals

- The ITk Layout Task Force plans for two more rounds of simulation before a decision can be made
- Step 1.6 [aiming for simulation launch this week]
  - Updates to **simulation**
    - Passive material even more realistic, including local supports for inclined modules
    - 100  $\mu\text{m}$  pixel sensor thickness inside the IST
  - Updates to **reconstruction**
    - Bug fixes: hole search tool, distortions, brem recovery, vertexing
    - Long clusters: Improved centroid,  $\theta$  measurement in Kalman filter (not by default)
  - **Layouts** considered, all covering  $|\eta| < 4$  [will include strips fix in layer 2: 52  $\rightarrow$  56 staves]
    - Extended
    - Extended with smaller innermost barrel radius at 33 mm
    - Fully inclined
    - Inclined inner pixel barrel
- Step 2.0

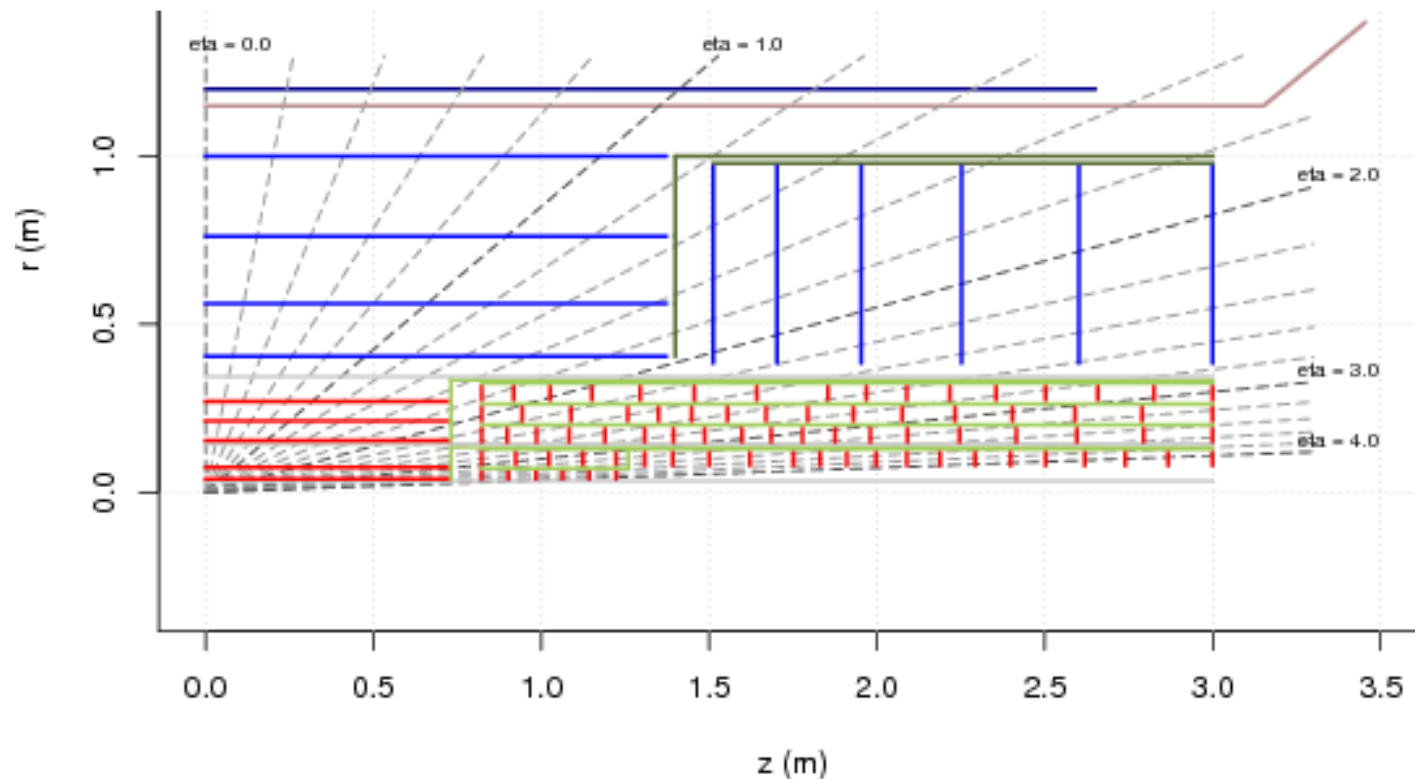


# Future goals

- The ITk Layout Task Force plans for two more rounds of simulation before a decision can be made
- Step 1.6
- Step 2.0 [timescale: 4 weeks to simulation launch]
  - Updates to **simulation**
    - Will simulate  $25 \times 100 \mu\text{m}^2$  pixels in each of the Step 2 layouts
    - As many of the improvements discussed earlier as possible
  - Updates to **reconstruction**
    - Final opportunity to understand reconstruction before layout decision
  - **Layouts** considered (all covering  $|\eta| < 4$ )
    - Extended, with re-optimized pixel endcap (8 forward pixel hits incl. long cluster)
    - Fully inclined, with re-optimized pixel endcap (9 forward pixel hits)
    - Barrel completion layer? ← if available in new simulation framework
    - “Conventional layout” with short barrel? ← idea yet to be presented at the LTF

# Conventional layout?

- Recent idea to propose a “conventional layout” with short barrel
  - Both current Extended and Inclined layouts have a long barrel, aiming to minimize the passive material before the first sensor for all  $|\eta| < 4$
  - Current consensus is that short barrel is a good low-risk “plan C”
  - Performance would need to be studied in full simulation to be considered seriously
    - undergraduate student working on it; would need help to get the passive material correct



# Conclusion

- ITk detector simulation has made **great progress** in the last year
  - We have reached first successful fully-simulated samples beyond Lol layouts
  - Realistic description of modules, and passive material with feedback from engineers
  - Digitization model improved for both strips and pixels
- Upgrade Tracking has also seen major improvements
  - Single-pass track reconstruction for  $|\eta| < 4$ , improved ambiguity solver, and more
  - Better understanding of figures of merit
- There is **still a lot of work to do**
  - Need to get urgent improvements and remaining bug fixes in for the Strips TDR
  - After the Strips TDR, pressure will start to rise towards the Pixel TDR
  - Lots of activity ongoing and planned in the simulation + performance group
  - There is always room for help!